Hysteresis properties of the amorphous high permeability $Co_{66}Fe_3Cr_3Si_{15}B_{13}$ alloy

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Hysteresis properties of the amorphous high permeability $Co_{66}Fe_3Cr_3Si_{15}B_{13}$ alloy

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The scaling law of minor loops was studied on an amorphous alloy $Co_{66}Fe_3Cr_3Si_{15}B_{13}$ with a very high initial permeability (more than 150000) and low coercivity (about 0.1 A/m). An analytical expression for the coercive force in the Rayleigh region was derived. The coercive force is connected with the maximal magnetic field $H_{\max}$ via the reversibility coefficient $\mu_i/\eta H_{\max}$. Reversibility coefficient shows the relationship between reversible and irreversible magnetization processes. A universal dependence of magnetic losses for hysteresis W_h on the remanence B_r with a power factor of 1.35 is confirmed for a wide range of magnetic fields strengths.
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I. INTRODUCTION

Regularities of changes of minor magnetic hysteresis loops depending on the amplitude of magnetic field or frequency can provide useful information on the magnetization processes in a magnetic material. Therefore, the scaling law of minor loops is intensively applied for the investigation of different magnetic materials.[1–7] In this regard, it is of interest to study regularities of parametric changes of a set of minor loops in the amorphous $Co_{66}Fe_3Cr_3Si_{15}B_{13}$ alloy with a very high initial permeability (more than 150000) and low coercivity (about 0.1 A/m).[8] High soft magnetic properties in this alloy are reached at the expense of a very low magnetic anisotropy constant. This is connected with the absence of crystallographic anisotropy in amorphous materials and of magnetoelastic anisotropy in the Co-based alloy because of a close-to-zero magnetostriction constant and low Curie temperature (about 415 K). The latter excludes a contribution to the magnetoelastic anisotropy from the directed magnetic ordering, which takes place as a result of atomic diffusion at a temperature lower than the Curie point, the diffusion being remarkably decelerated below 415 K. Amorphous alloy $Co_{66}Fe_3Cr_3Si_{15}B_{13}$ is produced on an industrial scale and is mainly used for high-precision current transformers.

In the work, the interrelation of parameters of minor magnetic-hysteresis loops (W_h is the area of static hysteresis loop, i.e., magnetic losses for hysteresis, B_r is the remanence, H_c is the coercivity, $B_{\max}$ is the maximal induction, and $H_{\max}$ is the maximal magnetic field) was investigated on the amorphous $Co_{66}Fe_3Cr_3Si_{15}B_{13}$ alloy in a wide range of magnetic fields H. Regions that present the logarithmic-scaled dependences of the parameters were distinguished; they correspond to the power function of the form

$$Y = rX^s. \tag{1}$$

Such a representation was for the first time used by Steinmetz for the dependence of magnetic losses for hysteresis on maximal induction.[9] Numerical changes in the power factor s in formula (1) are controlled by different types of the magnetization reversal process.[1,2,10]

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II. EXPERIMENT

The alloy $Co_{66}Fe_3Cr_3Si_{15}B_{13}$ was melt in a vacuum induction furnace. A 25 μm thick and 10 mm wide ribbon with amorphous structure was produced by the planar flow casting process. The ribbon was wound up onto ring-type cores with the 32 mm outer diameter and 20 mm inner diameter. The cores were subjected to optimum annealing at a temperature of 740 K for 1 h. Parameters of the DC hysteresis loop were determined by means of the point-by-point DC testing on the measuring and computing system MMKC-100-05 in the range of maximal magnetic induction B_{max} from 0.003 T to magnetic saturation.[11] Before measuring each minor loop, the sample was demagnetized by a decaying alternating magnetic field.

III. RESULTS AND DISCUSSION

In FIG. 1, the static minor loops of magnetic hysteresis are shown from which it is seen that the loop shape regularly changes from lens-like in the range of weak fields to elongated along the magnetic induction axis in the range of medium fields (in the range of maximal permeability). The parameters of minor loops are given in TABLE I. The results of measurements are placed in columns: B_{max} is the maximal induction, H_{max} is the maximal magnetic field, B_r is the remanence, H_c is the coercive force, W_h is the area of the static hysteresis loop (magnetic losses for hysteresis). The other values are calculated from the experimental data.

In a weak magnetic field, the permeability

$$\mu = \frac{B}{\mu_0 H} \tag{2}$$

changes insignificantly and therefore, can be expand in a Maclaurin series in the vicinity of $H = 0$. With only two first terms, we obtain

$$\mu = \mu(0) + \left(\frac{\partial \mu}{\partial H}\right)_{H=0} H. \tag{3}$$

Equation (3) is the Rayleigh law of magnetization expressed in the form[12,13]

$$\mu = \mu_i + \frac{1}{2}\eta H. \tag{4}$$

The first term in formula (4) represents the initial permeability μ_i, which is related to the contribution of reversible magnetization processes, and η is the Rayleigh constant related to irreversible magnetization processes.

Using the Rayleigh law, one can write out equations for the ascending and descending branches of magnetic hysteresis in the form

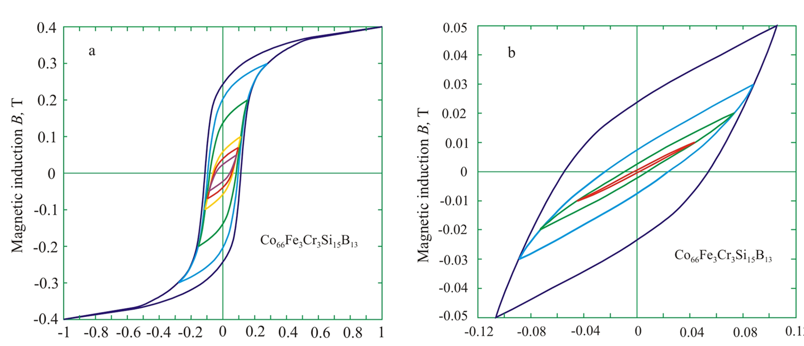

FIG. 1. Minor hysteresis loops of the alloy $Co_{66}Fe_3Cr_3Si_{15}B_{13}$ for different values of the maximal magnetic induction B_{max} (a, b).

TABLE I. Parameters of minor hysteresis loops of the amorphous alloy $Co_{66}Fe_3Cr_3Si_{15}B_{13}$.

$B_{\max}$, T	$H_{\max}$, A/m	B_r, T	H_c, A/m	W_h, J/m^3	μ	$B_r/B_{\max}$	$W_h/(B_r \cdot H_{\max})$	$W_h/(B_r \cdot H_c)$	$\eta \cdot 10^{-6}$, (A/m)$^{-1}$	$\mu_i/\eta H_{\max}$
0.003	0.0132	$0.6 \cdot 10^{-4}$	$2.56 \cdot 10^{-4}$	$2.3 \cdot 10^{-6}$	181000	0.02	2.90	150	0.74	18.5
0.005	0.0219	$1.6 \cdot 10^{-4}$	$6.8 \cdot 10^{-4}$	$9.7 \cdot 10^{-6}$	182000	0.03	2.77	89	0.55	15.1
0.0075	0.0325	$3.3 \cdot 10^{-4}$	0.0014	$2.7 \cdot 10^{-5}$	184000	0.045	2.52	58	0.48	11.8
0.01	0.043	$6.4 \cdot 10^{-4}$	0.0023	$6.2 \cdot 10^{-5}$	185000	0.065	2.25	42	0.47	9.2
0.02	0.083	0.0025	0.009	$4.44 \cdot 10^{-4}$	192000	0.125	2.14	20	0.46	5.0
0.03	0.108	0.0055	0.02	0.00128	221000	0.18	2.15	11.6	0.61	3.2
0.05	0.12	0.024	0.055	0.0071	332000	0.48	2.47	5.4	2.45	1.1
0.075	0.135	0.042	0.075	0.0148	442000	0.56	2.61	4.7	3.6	0.91
0.1	0.145	0.059	0.08	0.0225	549000	0.59	2.63	4.8	4.4	0.86
0.15	0.16	0.1	0.09	0.0404	746000	0.67	2.53	4.5	5.9	0.83
0.2	0.19	0.138	0.102	0.064	838000	0.69	2.46	4.6	5.6	0.79
0.3	0.30	0.204	0.104	0.102	796000	0.68	1.67	4.8	2.3	0.34
0.4	1	0.242	0.112	0.144	318000	0.61	0.60	5.3	–	–

$$B = (\mu_i + \eta H_{\max})\,\mu_0 H - \frac{1}{2}\eta\mu_0\left(H_{\max}^2 - H^2\right), \tag{5}$$

$$B = (\mu_i + \eta H_{\max})\,\mu_0 H + \frac{1}{2}\eta\mu_0\left(H_{\max}^2 - H^2\right). \tag{6}$$

After substitution of $H = H_{\max}$ into (5) obtain

$$B_{\max} = \mu_i\mu_0 H_{\max} + \eta\mu_0 H_{\max}^2. \tag{7}$$

In equations (5) and (6) with $H = 0$ the remanence is

$$B_r = \frac{1}{2}\eta\mu_0 H_{\max}^2, \tag{8}$$

and specifying $B = 0$, we determine the coercive force

$$\frac{H_c}{H_{\max}} = -\left(\frac{\mu_i}{\eta H_{\max}} + 1\right) + \sqrt{\left(\frac{\mu_i}{\eta H_{\max}} + 1\right)^2 + 1}. \tag{9}$$

The dimensionless value $\mu_i/\eta H_{\max}$ characterizes the interrelation of reversible and irreversible magnetization processes and, therefore it can be called reversibility coefficient. The area of the magnetic hysteresis loop is determined as

$$W_h = \frac{4\eta\mu_0 H_{\max}^3}{3} = \frac{8}{3}B_r H_{\max}. \tag{10}$$

The Rayleigh constant was calculated using numerical values of W_h and $H_{\max}$ by formula (10). As follows from TABLE I, in the amorphous alloy $Co_{66}Fe_3Cr_3Si_{15}B_{13}$ for $B_{\max} < 0.05$ T calculated values η vary slightly near the mean value $0.55 \cdot 10^6$ (A/m)$^{-1}$. In this region, there prevail reversible processes with the reversibility coefficient $\mu_i/\eta H_{\max} > 1$, and the hysteresis loops have a lens-like shape with a low remanence ratio $B_r/B_{\max} < 0.2$. The reversible magnetization process in the region of weak fields can be connected with the 180° domain wall bulging under the action of a magnetic field at the points where the wall is unpinned without tearing off the place of pinning.[14] The bulging of the wall without tearing-off and, consequently, the magnetization process would proceed until the magnetic field pressure becomes equal to the surface tension of the domain wall.

In FIG. 2, the dependences of $B_{\max}$, B_r, and H_c on the maximal magnetic field $H_{\max}$ are shown. It is seen that on the logarithmic scale, all the dependences are linear only in the Rayleigh region. The power factors s are close to the calculated values. For $B_{\max}$, the factor s is equal to 1 for the region in which the quadratic term in formula (7) can be neglected, i.e., provided that $\mu_i/\eta H_{\max}$ is by far larger than 1. For B_r and H_c, the factor s is equal to 2 in accordance with formulas (8) and (9).

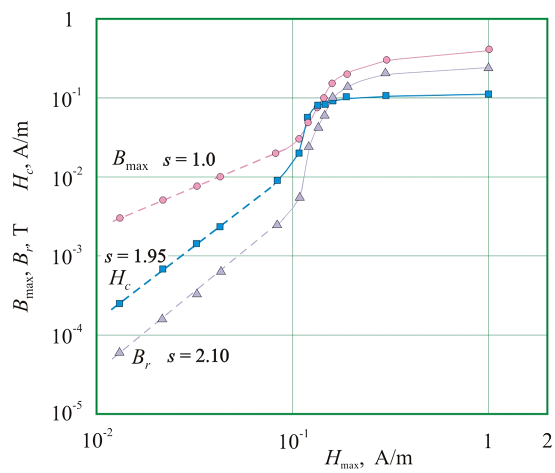

FIG. 2. Dependences of maximal induction B_{max}, remanence B_r, and coercive force H_c on the maximal magnetic field H_{max} for the amorphous alloy $Co_{66}Fe_3Cr_3Si_{15}B_{13}$.

Note that quadratic dependence of H_c obviously does not follow from formula (9), however, it can be ascertained from a graphic representation of the functional dependence (9) in the Rayleigh region.

In the dependences of the parameters of minor hysteresis loops on the maximal induction B_{max} on the logarithmic scale, one can find linear portions in both the region of weak magnetic field and where the permeability displays maximal growth (FIG. 3). Note that in the H_{max} curve there are two points in the region of decreasing permeability at $B_{max} > 0.2$ T that fall noticeably beyond the linear plot. At the same time, no decline of the B_r and H_c curves from linearity is observed. It is also seen from FIG. 3 that in the region of maximal permeability, the power factors s are significantly lower than in weak fields. In this region of the easiest magnetization reversal, the irreversible jump-wise motion of domain walls occurs, which results from sequential overcoming by the domain walls of local potential barriers.

The dependences of the magnetic losses for hysteresis W_h on the parameters of magnetic hysteresis loops are shown on the logarithmic scale in FIG. 4 and 5. As is seen, all the dependences change their slope at the boundary of the Rayleigh region except for the remanence B_r. In the Rayleigh region, the power factor for the dependences of W_h on B_{max} and H_{max} is close to 3, which corresponds to

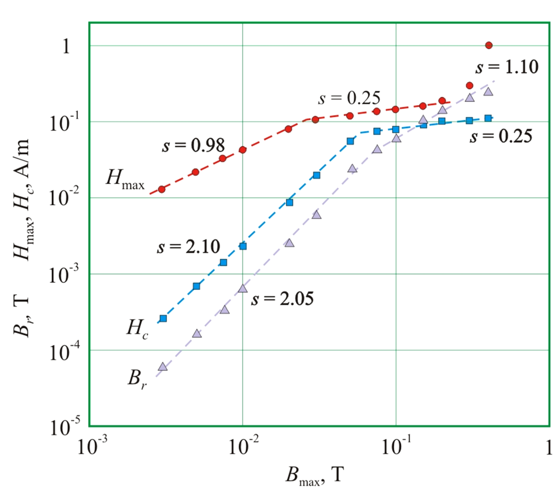

FIG. 3. Dependences of maximal magnetic field H_{max}, coercive force H_c, and remanence B_r on the maximal magnetic induction B_{max} for the amorphous alloy $Co_{66}Fe_3Cr_3Si_{15}B_{13}$.

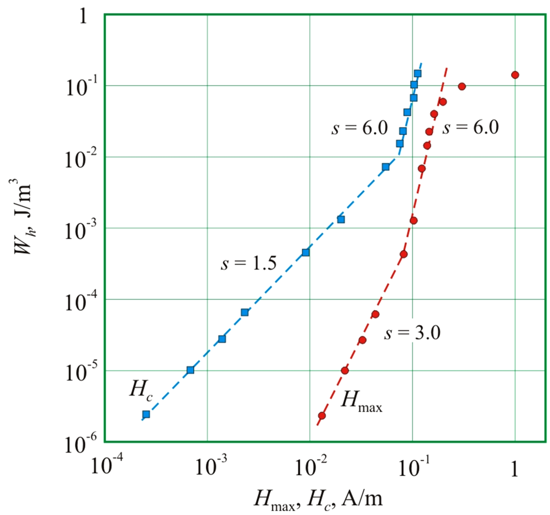

FIG. 4. Dependence of magnetic losses for hysteresis W_h on the maximal magnetic field H_{max} and coercive force H_c for the amorphous alloy $Co_{66}Fe_3Cr_3Si_{15}B_{13}$.

formula (10). The dependence of W_h on H_c with the factor 1.5 becomes evident if to substitute in formula (10) an empiric expression $H_c \sim H_{max}^{1.95}$ shown in FIG. 2.

In the region of the maximal permeability growth, the power factor for the dependence of W_h on B_{max} on the logarithmic scale is equal to 1.5, which is close to the classical value 1.6 obtained by Steinmetz. The factor $s = 6$ for the dependence of W_h on H_{max} can be obtained if to take into account the relationship $H_{max} \sim B_{max}^{0.25}$in FIG. 3.

The power factor s for the dependence of the hysteresis losses on the remanence on the logarithmic scale is equal to 1.35 and remains constant up to the point of bending of the magnetization curve where the displacement of 180° domain walls starts prevailing. The same dependence of W_h on B_r was earlier discovered in other magnetic materials.[3–6] As follows from TABLE I, the hysteresis losses in the Rayleigh region are proportional to the product $B_r \cdot H_{max}$, whereas in the region of the maximal permeability growth, to the product $B_r \cdot H_c$, i.e., to the remanence in both cases. The ground for this is the shape of the hysteresis loop. From the geometrical point of view, up to the bend of the magnetization curve (to the appearance of the beak in the loop), the height of the loop is remanence

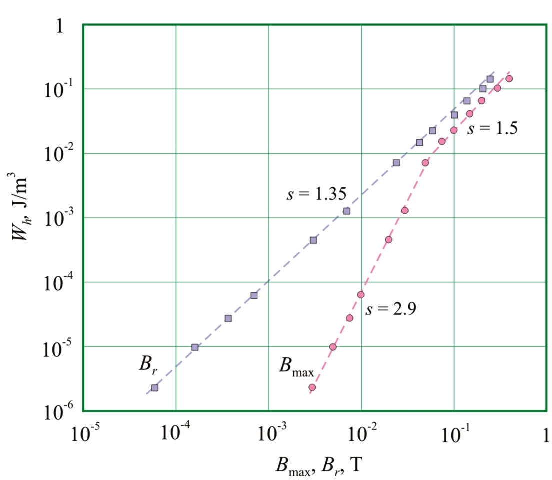

FIG. 5. Dependence of magnetic losses for hysteresis W_h on the maximal induction B_{max} and remanence B_r for the amorphous alloy $Co_{66}Fe_3Cr_3Si_{15}B_{13}$.

B_r, and the width, either $H_{\max}$ in the Rayleigh region or H_c in the region of the maximal permeability growth.

IV. CONCLUSION

In the work, an interrelation of the parameters of minor hysteresis loops was investigated for the case of the amorphous alloy $Co_{66}Fe_3Cr_3Si_{15}B_{13}$ with a very high initial permeability (more than 150000) and low coercive force (about 0.1 A/m). An analytical expression for the coercive force in the Rayleigh region is derived. The coercive force is connected with the maximal magnetic field $H_{\max}$ via the reversibility coefficient $\mu_i/\eta H_{\max}$. Reversibility coefficient shows the relationship between reversible and irreversible magnetization processes. If the reversibility coefficient exceeds 1, the reversible magnetization processes are predominant and vice versa. The linear curves of the interrelation of the hysteresis loop parameters are plotted on the logarithmic scale for the Rayleigh region and region of the maximal permeability growth. The universality of the dependence of the magnetic losses for hysteresis W_h on the remanence B_r with the power factor 1.35 is confirmed. It is shown that the magnetic losses for hysteresis in the amorphous alloy $Co_{66}Fe_3Cr_3Si_{15}B_{13}$ are proportional to the product $B_r \cdot H_{\max}$ in the Rayleigh region and to $B_r \cdot H_c$ in the region of the maximal permeability growth, i.e., to the remanence in a wide range of magnetic fields.

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